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Research Article

MECHANICS AND MATERIALS FOR NEXT GENERATION BIOINSPIRED SOFT ROBOT

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Abstract

In conventional robotics, the technological research focuses on strength and functionality of robots. Recently, out of these perspective, soft robot, which is new shape of robots inspired from biological systems attracts intensive interest in fields of robotics. Inspired from nature, we could improve the mechanical properties of conventional robots and impart new kinds of biological functions to robots. Many innovative strategies have been developed in recent years to design soft components and systems that realizes natural actuations of bioinspired robot. Soft robots consist of soft materials and are actuated by various kinds of mechanical principles. There are several advantages of soft robots compared to the conventional robots; safe human-machine interactions, adaptive conformability to wearable devices, useful biological properties from organism etc. Due to the unique features and advantages, soft robots have a considerable range of applications. The purpose of this study is investigation of state of art technologies regarding mechanical and material aspects of soft robots. This review was written in three fundamental sections: i) Materials for soft robotics, ii) fundamental mechanics of soft materials and, iii) mechanical principles of actuation. The promising soft materials can be categorized simply in four types according to softness and functions: hydrogel, elastomer, shape memory polymer and self-healing polymer. These materials have softness and deformation freedom, which has potential to provide natural movements of robot enabling imitation of biological movements. To analyze it in scientific method, we investigate the several mechanical standards and principles of robot actuation in mechanical aspects. In the future, all robots would evolve closer to biological lives.

Keywords: Mechanics, Robot.

INTRODUCTION

Current robots are developed with rigid-bodied designs with discrete joints in order to support large loads. In particular, the stiff materials such as plastics, composites, metals, and ceramics used for structural and functional supporter, packaging, motors, industry robots show following advantages: i) highly load bearing and can support large mechanical work, ii) can maintain fixed mechanical or electrical properties under extreme forces and iii) enable precision positioning and motion control by rigidly rotating displacements in connection joint. However, these hard and heavy robots require precise, complex sensing and control systems to operate in an uncontrolled environment. Therefore, the field of soft robotics was brought up to the surface to realize the adaptive and flexible movement. With the use of materials with an elastic modulus, soft robots are designed to be light and compliant. These properties allow soft robots to have the potential to change the paradigm of robots in fields that require sophisticated movements or flexibility by removing the joint in order to combat uncertainties caused in natural environments. In general, the actuator system needs power from battery, however, some principles allow soft robot to move by external stimuli such as heat, light, electric fields, and magnetic fields, which trigger large deformations like isotropy/anisotropy swelling of soft materials. In this review, we will first review some of promising soft materials. In this section, many of the material technologies used to create the artificial muscle, nervous tissue, and skin used for soft robots will be introduced including elastomers, soft polymer composite, shape memory polymer and self-healing polymer. In next section, we simply introduce the mechanical aspects of materials and investigate the a few main principles of soft actuator. Different actuation technologies have been proposed and are widely in use. Starting from pneumatic actuation, which is most of common strategy for simple actuation, vacuum actuation, shape memory actuation and electroactive polymer actuation will be shown.

Fundamental mechanics of soft materials

Unlike conventional rigid materials for robot, soft materials have changed the paradigm of future robotics, specifically in attractive movements, robustness under deformation and new functions more like biological skins. To evaluate the performances of materials applied to soft robotics, we need mechanical standards and methods of analysis. We would review the mechanical basis of soft materials in this section.

Young's modulus

Young's modulus is important standard for investigating the softness of materials. It also describes the elastic properties of a material undergoing tension or compression in only one direction. Young's modulus is a measure of the ability of a material to withstand changes in length when under strain such as tension or compression. Sometimes referred to as the modulus of elasticity, Young's modulus is equal to the longitudinal stress divided by the strain. Stress and strain may be described as follows in the case of a rubber under tension (Figure 1). when a stretchable rubber of cross-sectional area A is pulled by a force F at each end, the bar stretches from its original length L_0 to L with simultaneously decreased cross section. The stress could be obtained by tensile force divided by the cross-sectional area, or F/A. The strain or relative deformation is the change of length, $L - L_0$, divided by the initiallength, or $(L - L_0)/L_0$. Thus Young's modulus may be expressed mathematically as$(F \times L_0)/A \times (L - L_0)$.

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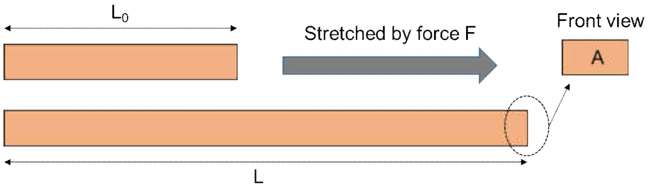

Figure 1. Deformation of soft material in lateral direction, *F*: force, *A*: cross sectional area, L_0: origin length, *L*: stretched length

This is a specific form of Hooke's law of elasticity. In conventional metallic materials with elastic design (spring), the young's modulus is almost constant. However, to explain the mechanical properties of soft materials by using this theory, we have to assume that the volume of materials is not constant because the internal polymer chains undergo dynamical movements under deformation (Fredrickson, 2001). So, different from perfectly elastic materials like metallic spring, the value of stress/strain in the soft materials is not constant. As shown in graph in Figure 2, the young's modulus of soft materials including rubber, hydrogel or polymer are determined in first linear region. Beyond elastic region in the graph, the value of stress/strain is changed and it means that the soft materials lose the elasticity.

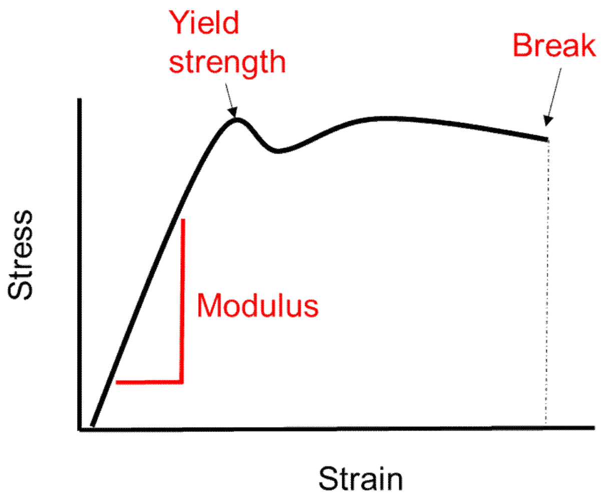

Figure 2. Strain-Stress graph showing mechanical property

Toughness

The ability of materials to deform over elastic region and to absorb energy in the process before fracture is called toughness. As mentioned in previous section, the polymer chains in the soft materials could move dynamically in the spaces of matrix under deformation. The external stress could be absorbed by moving of these mobility of polymer chains in all region of strain. So, the toughness is resistance to fracture of material and could be calculated by area under the stress strain curve from a tensile test.

Mechanical principles of actuation

Different actuation strategies have been researched and are widely in use. Typical soft grippers employ actuators that make them adapt to objects of various shapes. Due to elastic deformability, various kinds of mechanical mechanisms are available, which are very useful to soft robotics. In this section, we address various kinds of actuation mechanism starting from pneumatic actuation.

Pneumatic actuation

The most common kind of actuation utilized in soft robots to grasp diverse items by applying positive pressures is pneumatic actuation. It is based on pressurizing soft chambers that have been purposefully created in order to have pre-set deformations, including bending. This kind of actuation has been used by researchers for a variety of focused applications. For the purpose of actuating soft grippers made up of finger-like elements, Lee et al. utilized pneumatic type of soft bending actuators formed of air chambers and constraint layer (Lee *et al.,* 2020). In order to achieve the conformable grabbing with low contact pressure and strong lifting force, stiffness patterning was used to arrange nodes of various stiffnesses in a particular way in the actuator's constraint layer, which controls an asymmetric deformation. Nguyen et al. used bistable buckling springs, which can sustain two stable states depending on the energy input, to pneumatically actuate a robotic finger to control it in three stable states. By using two bi-stable springs of a soft and rigid nature in the finger, they considered three stable states of grasping: open, pinch, and wrap (Nguyen *et al.,* 2020). In order to regulate the bending angle of a soft robotic finger, Kim *et al.* substituted the compressor with an origami pump powered by tendons. Soft pneumatic actuators have limits in terms of low actuation speed and fingertip force. To overcome this challenge, a hybrid PneuNet actuator was reported (Kim and Cha, 2020). The round edge shape between rigid andsoft material was responsible for high fingertip force, while the fast PneuNet with a high number of chambers and channels enhanced the actuation speed of the gripper. In this way, using pneumatic actuation mechanism, many types of soft actuators have been developed for next generation robotic hands.

Shape Memory Actuation

In soft robotics, researchers have researched the materials to implement cyclic movement without degradation. Perfect recovery of materials requires high elastic modulus, which diminish the softness. Shape memory alloy is novel materials for bio-inspired soft robotics. Due to their advantages in terms of low noise, high force to weight ratio, small size, and other factors, shape memory alloys (SMA) have also been employed in soft grippers for actuation. Hadi *et al.* devised a module that, in addition to having only two conditions of on and off through SMAs, could reach any desired set point by utilizing a suitable control approach. In other words, the module could be configured anyway you wanted. The SMA springs were heated either individually or collectively to provide a differential actuation system (Hadi *et al.,* 2016).

Conclusion

Actuation is a significant difficulty for soft robots in general since it is impossible to achieve the required functionality without the optimization of actuation technology. Based on principles of mechanics and standards, many technical actuators have been developed. The most common method is pneumatic actuation, which offers strong gripping forces and enables the user control to achieve the actuator's desired shape. These actuators respond quickly and without any friction issues. Additionally, the control is simple, which is why it is more frequently utilized than the alternative techniques. However, it is challenging to miniaturize them, and leakages make them susceptible to failure in tests. SMAs are a common choice for powering various soft systems because of their shape-changing property caused by temperature stimuli. High ratio of power to weight through ohmic heating, SMAs are easily driven by electric current. They feature low driving voltages, little size, high distortions, smooth motion, and minimal noise production. They also have simple architectures. They are not, however, preferred in applications that need for quick response because of their slow response. They also exhibit negative tiredness traits. In the future, soft actuators based on simple mechanics will be the main stream in soft robotics for next generation robotics.

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